Forest Ecology and Management 281 (2012) 130–139

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Soil and sugar maple response 15 years after dolomitic lime application

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ARTICLE INFO

Article history:
Received 3 May 2012
Received in revised form 13 June 2012
Accepted 16 June 2012
Available online 20 July 2012

Keywords:
Forest liming
Acer saccharum
Dieback
Regeneration
Growth
Nutrition

ABSTRACT

Dolomitic lime ($CaMg(CO_3)_2$) was applied in 1994 at rates of 0–50 Mg ha^{-1} to sugar maples (SMs) (*Acer saccharum* Marsh.) in a base-poor and declining northern hardwood stand subjected to a high level of acid deposition in Quebec. The soil chemistry and the SM nutrition, growth, crown vigor, and regeneration status were evaluated 15 years after treatment. The soil chemical properties still responded strongly to lime after 15 years. Similarly, the foliar Ca and Mg concentrations were still higher for treated trees relative to the control trees. After 15 years, the mean crown dieback of trees decreased quadratically with the lime rate, from 39% for the control trees to a value of 1–3% for the lime rates of 5 Mg ha^{-1} and higher. Additionally, the stem basal area increment for the limed trees was nearly double that of the unlimed trees in 2009. The lime application was also beneficial to the SM regeneration. The overall SM seedling density increased with the lime rate, being nearly twice as much in the 50 Mg ha^{-1} (32 seedlings m^{-2}) compared with the controls (16 seedlings m^{-2}). The proportion of the SM seedlings to all of the other species increased quadratically from 22% in controls to more than 55% in the 5–50 Mg ha^{-1} treatments. In contrast, the proportion of competitive species decreased quadratically with the lime rate, including American beech (*Fagus* grandifolia Ehrh.) for which the proportion in the treated plots (24%) was nearly half the proportion observed in the controls (46%). However, increase in stem density of regeneration and canopy closure in response to lime application limit the development of the regeneration which did not benefit in terms of diameter and height. These results show that a single lime addition has long-term beneficial effects on the soil chemistry and the SM nutrition, vigor, growth, and regeneration in base-poor and declining northern hardwood stands. Moreover, the results confirm that liming is an essential tool to restore the SM representation and health in acidic and base-poor soils.

1. Introduction

Numerous studies performed during recent decades have shown that decreasing sugar maple (SM) (*Acer saccharum* Marsh.) vitality remains a major concern in many areas of the northeastern North America, including New York (Hallett et al., 2006), Pennsylvania (Long et al., 1997, 2009, 2011; Horsley et al., 2000, 2002; Bailey et al., 2004), the New England states of New Hampshire and Vermont (Wilmot et al., 1995, 1996; Hallett et al., 2006; Schaberg et al., 2006; Gavin et al., 2008) in the USA as well as Quebec (Duchesne et al., 2002, 2003; Duchesne and Ouimet, 2008; Moore and Ouimet, 2006, 2010; Ouimet et al., 2008) and Ontario (Ryan et al., 1994; McLaughlin, 1998; McLaughlin et al., 2000; Watmough and Dillon, 2003; Tominaga et al., 2008; Watmough, 2010) in Canada.

The SM is established as being very sensitive to soil acidity (Thornton et al., 1986; Ouimet et al., 1996a). In survey plots in Vermont, Wilmot et al. (1995) observed a strong correlation between the soil pH and SM dieback. Other studies have suggested that acid deposition has accelerated the loss of available Ca from the soils with a low acid-buffering capacity in northern hardwood stands (Likens et al., 1998; McLaughlin, 1998; Houle et al., 1997; Sharpe, 2002; Bailey et al., 2005; Long et al., 2009). Duchesne et al. (2002) showed that the appearance of the SM decline phenomenon and associated growth reduction in Quebec can be related, at least in part, to the soil acidification and acid deposition levels.

In this context, it is unsurprising that many studies on SM dieback suggested that base cation deficiency, and particularly Ca deficiency, was a cause of the tree growth reduction and decline (Sharpe and Sunderland, 1995; Wilmot et al., 1995; Long et al., 1997, 2009; Bailey et al., 2004; Schaberg et al., 2006; Huggett et al., 2007; Watmough, 2010). Moreover, a positive growth and vigor response of SM to liming or Ca addition in base-poor northern hardwood stands demonstrated that the Ca deficiency was linked to SM decline in these ecosystems (Wilmot et al., 1996; Moore and Ouimet, 2006, 2010; Juice et al., 2006; Huggett et al., 2007; Ouimet et al., 2008; Long et al., 2011).

Although the short-term (Ouimet and Fortin, 1992; Wilmot et al., 1996; Moore et al., 2000; Juice et al., 2006; Moore and

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http://dx.doi.org/10.1016/j.foreco.2012.06.026

Ouimet, 2010) and mid-term (Long et al., 1997; Moore and Ouimet, 2006; Huggett et al., 2007; Ouimet et al., 2008) beneficial effects of fertilization with base cations on SM have been demonstrated, only one study on the long-term effect of this treatment is available (Long et al., 2011: 23 years). Currently, only four advanced trials using Ca (with or without Mg) components are still studied in northeastern North America: the first in Pennsylvania, USA (1988 to present) (Long et al., 2011); the second in Quebec, Canada (1994 to present) (Moore and Ouimet, 2006); the third in New Hampshire, USA (1999 to present) (Juice et al., 2006); and the fourth also in Quebec (2002 to present) (Moore and Ouimet, 2010). However, the liming trial in Quebec represents the only study that has documented the effect of economically operational rates (0.5, 1, 2, 5 Mg ha^{-1}) of a widely available Ca fertilizer on soils and SM. The goal of this study was to help fill this knowledge gap by documenting the long-term (15 years) effect of the 1994 liming experiment (Moore et al., 2000; Moore and Ouimet, 2006) on the soil and the SM nutrition, crown dieback, growth and regeneration in a declining northern hardwood stand situated in acidic and base-poor soils in Quebec, Canada.

2. Materials and methods

2.1. Site description

The experimental stand (46°57′N, 71°40′W) is located in the Duchesnay Experimental Forest, approximately 50 km northwest of Quebec City (Quebec). The elevation varies between 270 and 390 m. The average slope is approximately 10%. The mean annual temperature and annual precipitation (1960–1990) are 3.4 °C and 1300 mm, respectively. The vegetation is dominated by SM in addition to yellow birch (*Betula alleghaniensis* Britt.) and American beech (AB) (*Fagus grandifolia* Ehrh.). According to the *Canadian System of Soil Classification* (Canada Soil Survey Committee, 1998), the soil is classified as a stony, sandy loam Orthic Ferro-Humic Podzol. The humus is of moder type, and the surface deposit is a very acidic and stony glacial till derived from the granitic gneiss bedrock of the Canadian Shield.

2.2. Stand conditions and disturbance history

The Lake Clair Watershed, located near the experimental liming site, is among the catchments in northeastern North America where acid deposition continue to acidify soils, with relatively high net soil Ca losses (Watmough et al., 2005). Over the 15-year period of the study (1994–2009), the atmospheric NO_3^-, NH_4^+, SO_4^{2-}, and H^+ loads in bulk deposition were estimated at 22, 5, 23 and 0.5 kg ha^{-1} yr^{-1}, respectively. During this period, neither severe insect defoliation nor frost or ice damage was observed in this area. However, relatively short drought episodes occurred during the summers of 1995 and 2002 but without lasting growth reductions. The last forest cutting in the experimental area was a thinning, which occurred in the 1940s.

The foliar Ca concentrations for unlimed SM in the liming experiment were among the lowest in northeastern North America (cf. Moore and Ouimet, 2010). The low availability of Ca in this ecosystem is probably attributable to the combination of high levels of acid deposition, significant Ca leaching, and relatively low Ca replenishment through mineral weathering in the soil (Houle et al., 1997; Ouimet and Duchesne, 2005).

The dieback rates of selected trees in 1994 (before liming) were low (<7%, Fig. 3). These low rates can be explained by the selective choice of SM trees among the healthiest available to maximize the long-term monitoring for this liming experiment.

2.3. Experimental design

In the stand, 98 SM trees were selected, numbered and treated randomly in the fall of 1994 (14 replicates for controls and 12 for the seven other treatments; see below). Their diameter in 1994 was 30.9 ± 5.6 cm (mean ± SE; range = 20.0–44.0 cm). The dolomitic lime ($CaMg(CO_3)_2$) of agricultural grade, containing 22% of Ca and 12% of Mg, was applied manually within a 5-m radius of each tree during the last week of August 1994, after cutting and removing the entire understory throughout the same radius to reduce the variability of understory abundance and to ensure the uniform spreading of lime. No other tree stem was within the 5-m radius around the SM trees. A total of 8 lime rates were applied (0, 0.5, 1, 2, 5, 10, 20 and 50 Mg ha^{-1}). Additional details on the experimental design can be found in Moore et al. (2000).

Foliage sampling was performed in mid-July before the treatment (1994) and in mid-August for the years following the treatment (1995–1998, 2002, 2004, and 2009). The foliar nutrient concentrations were used to evaluate the nutrient status.

In October 2009, the soil around each tree was sampled in duplicate with a bi-partite auger (Eijkelkamp model 05.02). The forest floor was separated from the first 10 cm of mineral soil. The samples were pooled for each horizon and tree, air-dried, and passed through a 2-mm sieve prior to physico-chemical analyses.

Two increment cores were taken from each tree after the growing season in October 2009 to measure the tree radial growth. The annual ring width measurements were performed using the WinDendro version 6.1D software (Régent Instruments Inc., 2009) and validated with the signature rings. The ring width values were converted to basal area increments (BAIs) using the following equation:

$$BAI_t(cm^2) = \pi(R_t^2 - R_{t-1}^2)$$

where R is the tree radius (cm), and t is the year of tree-ring formation.

The dieback was evaluated from 1994 to 1998 and in 2002, 2004, and 2009 by estimating the percentage of the missing crown foliage (5% class intervals) from the careful visual inspection by the same two experienced observers. The crown assessment was performed the same day as the foliage sampling.

Two inventory types were made in summer 2009 to evaluate the regeneration response to liming. First, the regeneration stems were numbered, and their diameter (at 15 mm from the surface of the forest floor) and height were measured in four circular sub-plots of 0.20 m^2 (radius 25 cm) located on cardinal points at 2.5 m from the center of each tree; the total area was 0.80 m^2 per plot, representing 1% of the total plot area. Second, the species, height and stem diameter at 15 cm from the forest floor surface for the ten taller regeneration stems were measured in each 5-m radius plot.

2.4. Chemical analyses

The soil pH was measured with water using a soil:solution ratio of 1:2.5 (w:w). The organic matter content was determined by loss-on-ignition (Nelson and Sommers, 1982) and organic C by dry combustion (LECO). Exchangeable cations (Ca, Mg, K, Na, Al, Mn, Fe) were extracted with an unbuffered NH_4Cl (1 M, 12 h) solution and measured by inductively-coupled plasma emission spectrophotometry (ICP). The exchangeable acidity was evaluated by summing the H^+ (measured by pH probe), Al, Mn, and Fe concentrations of the extracts. The effective cation exchange capacity (CEC) was computed as the sum of exchangeable base cations and acidity. The concentrations are reported on a dry-weight basis.

Base saturation (BS) was calculated as the proportion of CEC as base cations.

The collected leaves, approximately forty from each tree, were initially dried at 65 °C and then ground to <250 μm. Nitrogen (N), P, K, Ca, Mg, manganese (Mn) and aluminum (Al) concentrations were determined by digesting 500 mg of foliage in hot concentrated H_2SO_4. Following digestion, N concentrations were measured by titration (Kjeltec Tecator 1030), while the other element concentrations were measured by atomic emission spectrophotometry (Perkin Elmer Plasma Model 40). Replicate samples were run for every 20 measurements and homemade reference tissue samples were run for every 40 measurements. Lab results laid always within ±10% of the values for those QA/QC samples. The foliar Al concentrations were always found to be less than the detection threshold (0.03 mg kg^{-1}).

2.5. Statistical analyses

Given that the short-term (Moore et al., 2000) and mid-term (Moore and Ouimet, 2006) results of this liming experiment were published previously, the main focus of this paper is to evaluate the 15-year response of SM to liming.

The soil data were analyzed using a generalized least squares (gls) model, which allowed for a heterogeneity correction with differing variances according to lime dose. We used the "nlme" package of the R software (Pinheiro et al., 2012) to perform these analyses.

The foliar concentrations, crown dieback and relative stem BAI (% of 1991–1994 values) were analyzed for 2009 only, using a one-way analysis of variance (ANOVA), with the liming rate as the main treatment. For the foliar analyses, the corresponding 1994 covariable was used, when applicable. To account for the variability of the tree growth between treatments before liming, the BAI for 1995–2009 and for 2009 only were adjusted with the pre-treatment BAI using the 1991–1994 BAI as covariable to provide the adjusted BAI means. These statistical analyses were performed using the SAS MIXED procedure (SAS Institute, 2002).

The effects of the lime treatment, the species (SM, AB, and others), and their interaction on the abundance, height and diameter of regeneration were examined by an ANOVA using the general linear model procedure (PROC GLM) in SAS (SAS Institute, 2002). The effects of the lime treatments on the average height and diameter of the ten taller regeneration stems were also examined.

Additionally, orthogonal polynomial contrasts were performed to separate the linear and quadratic components of the trend across treatments.

3. Results

3.1. Soil response to liming

The soils still responded strongly to lime after 15 years (Table 1). The forest floor pH, organic carbon, organic matter, total N concentrations and C/N ratio changed linearly with the lime rate ($P < 0.001$). The forest floor pH increased from 3.95 ± 0.08 (mean ± SE) for the control treatment up to 6.25 ± 0.12 for the 50 Mg ha^{-1} lime treatment after 15 years, while the carbon, organic matter and total N concentrations decreased by 20–30% between these two treatments ($P < 0.001$). The organic carbon concentrations, however, decreased slightly more rapidly with the lime rate than the total N concentrations did, resulting in a statistical but ecologically non-significant increase in the C/N ratio with the lime dose in this soil horizon after 15 years. The exchangeable Ca and Mg concentrations, as well as the CEC and BS, increased in a quadratic fashion on the forest floor with the lime rate, while the exchangeable K, Na, and acidity concentrations decreased ($P \leqslant 0.001$) (Table 1).

Within the first 10 cm of the mineral soil, the pH, carbon, organic matter, and total N concentrations changed in a manner similar to the forest floor. The mineral soil pH increased from 4.22 ± 0.08 (mean ± SE) for the control treatment up to 5.76 ± 0.16 for the 50 Mg ha^{-1} lime treatment after 15 years, while the organic carbon, organic matter and total N concentrations decreased by 20–30% between these two treatments ($P < 0.043$). However, the C/N ratio in this horizon did not change with the lime dose after 15 years. The exchangeable Ca and Mg concentrations and the CEC increased in a linear fashion with the lime rate in the first 10 cm of mineral soil, while the BS increased strongly in a quadratic fashion with the lime rate ($P < 0.001$) (Table 1). In this soil horizon, the exchangeable K and acidity concentrations followed a quadratic decrease with the lime rate, with the higher lime rates reaching approximately 60 and < 20% of the exchangeable K and of the acidity concentrations of the controls, respectively ($P < 0.001$). The exchangeable Na concentrations were not influenced by liming in this soil horizon after 15 years ($P = 0.477$).

3.2. Effect of liming on SM

3.2.1. Foliar concentrations

Fifteen years after treatment, the foliar Ca and Mg concentrations increased quadratically with the liming rate ($P \leqslant 0.014$) (Fig. 1; Table 2). Compared with the control treatment, the foliar Ca and Mg concentrations were more than two times higher in the 20 and 2 Mg ha^{-1} lime treatments, respectively. The foliar K and Mn concentrations decreased linearly ($P \leqslant 0.015$) with the liming rate ($P \leqslant 0.014$) (Fig. 1; Table 2). However, if only economically sound doses are used for the analysis (0, 0.5, 1, 2, 5 Mg ha^{-1}), the effect on the Mn foliar concentrations was no longer present ($P = 0.482$). No effect of liming was observed for the foliar N and P concentrations after 15 years. Additionally, a slow decline in the foliar Ca (for the 10 Mg·ha^{-1} doses and less) and Mg (for the 0.5 and 1 Mg·ha^{-1} doses) concentrations in SM was observed over the years (Fig. 2).

3.2.2. Crown dieback

After 15 years, mean crown dieback of trees decreased quadratically with the lime rate, from 39% for control trees to a value of 1–3% for lime rate of 5 Mg ha^{-1} and over ($P = 0.005$; Fig. 1). In 2009, the ten trees with the greatest crown dieback rates (100% = dead tree) were among the controls (40–100%, $n = 6$) or had the lower lime rates (0.5 Mg ha^{-1}, 100%, $n = 2$; 1 Mg ha^{-1}, 100%, $n = 1$; 2 Mg ha^{-1}, 100%, $n = 1$). Over the years, a high and steady increase in the dieback rate was observed for the unlimed trees and a low increase with the lower (0.5, 1, 2 Mg ha^{-1}) lime doses, while the dieback rates have remained low with the higher doses (Fig. 3).

3.2.3. Basal area increment

The mean 1995–2009 and the mean 2009 tree BAI were 80% and 86% higher, respectively, for the limed trees than for the unlimed ones ($P \leqslant 0.001$). However, no linear or quadratic trend in the BAI was detected for the liming rates (1995–2009: $P \geqslant 0.052$, data not shown; 2009: $P \geqslant 0.170$) (Fig. 1); however, if only economically sound doses are used in the analysis (0, 0.5, 1, 2, 5 Mg ha^{-1}), a positive linear trend is observed (1995–2009: $P < 0.001$; 2009: $P = 0.001$). Overall, the BAI data showed that the negative trend observed between 1970 and 1994 is still observed for the unlimed trees (Fig. 4). This negative trend in trees was reversed after liming.

3.2.4. Regeneration

The mean regeneration stem density and the proportion of SM, AB, and all other species pooled together for each lime treatment are presented in Fig. 5. Fifteen years after treatment, the overall

Table 1
Fifteen-year effect of dolomitic lime rate on soil physico-chemical properties at Duchesnay.

Lime rate ($Mg\ ha^{-1}$)	pH	Carbon ($g\ kg^{-1}$)	Organic matter ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	C/N	Exchangeable cations ($cmol\ kg^{-1}$)						BS (%)
						Ca	Mg	K	Na	Acidity	CEC	
Forest floor												
0	3.95	343	629	16.58	20.6	10.77	2.18	1.15	0.07	3.38	17.54	78.32
0.5	4.10	360	684	18.69	19.5	10.21	2.81	1.43	0.07	4.59	19.12	75.96
1	4.10	410	729	19.05	21.7	13.09	5.20	1.31	0.07	3.18	22.86	84.60
2	4.35	333	628	17.15	19.4	12.61	4.56	1.12	0.09	3.21	21.59	81.19
5	4.40	354	682	17.69	19.9	17.48	9.38	1.31	0.08	1.28	29.53	94.46
10	5.00	326	636	16.61	19.6	25.15	12.88	1.03	0.08	0.45	39.58	98.48
20	5.76	290	522	13.53	21.4	25.57	16.32	1.03	0.06	0.19	43.17	99.47
50	6.25	271	457	10.95	24.4	28.00	16.83	0.59	0.05	0.10	45.56	99.77
RSE[a]	0.40	93.97	149.50	4.19	3.04	5.62	4.15	0.42	0.03	0.001	6.97	0.03
$P > F$	<0.001L[b]	0.001L	<0.001L	<0.001L	<0.001L	<0.001Q[c]	<0.001Q	<0.001L	<0.001L	<0.001Q	<0.001Q	<0.001Q
First 10 cm of mineral soil												
0	4.22	93	175	4.35	21.4	1.35	0.31	0.21	0.03	5.44	7.34	24.56
0.5	4.46	112	218	5.77	19.9	1.03	0.41	0.28	0.04	5.33	7.08	24.80
1	4.44	96	191	4.63	21.1	1.41	0.56	0.21	0.03	5.69	7.90	25.38
2	4.66	106	209	5.32	20.4	1.61	0.64	0.22	0.04	5.27	7.77	30.99
5	4.64	101	193	4.04	22.6	2.32	1.61	0.17	0.03	3.98	8.11	44.33
10	4.90	73	139	3.61	20.2	2.68	2.27	0.15	0.03	2.55	7.67	63.68
20	5.25	72	137	3.35	21.6	3.97	4.80	0.14	0.03	1.02	10.56	90.05
50	5.76	71	140	3.26	21.9	6.86	7.45	0.11	0.04	0.54	15.00	93.63
RSE	0.57	52.70	41.41	0.91	1.98	2.52	3.29	0.02	0.03	1.18	4.75	17.02
$P > F$	<0.001L	0.043L	0.008Q	0.004Q	0.387	<0.001L	<0.001L	<0.001Q	0.477	<0.001Q	<0.001L	<0.001Q

[a] RSE: Model residual standard error.
[b] L = Linear effect.
[c] Q = Quadratic effect.

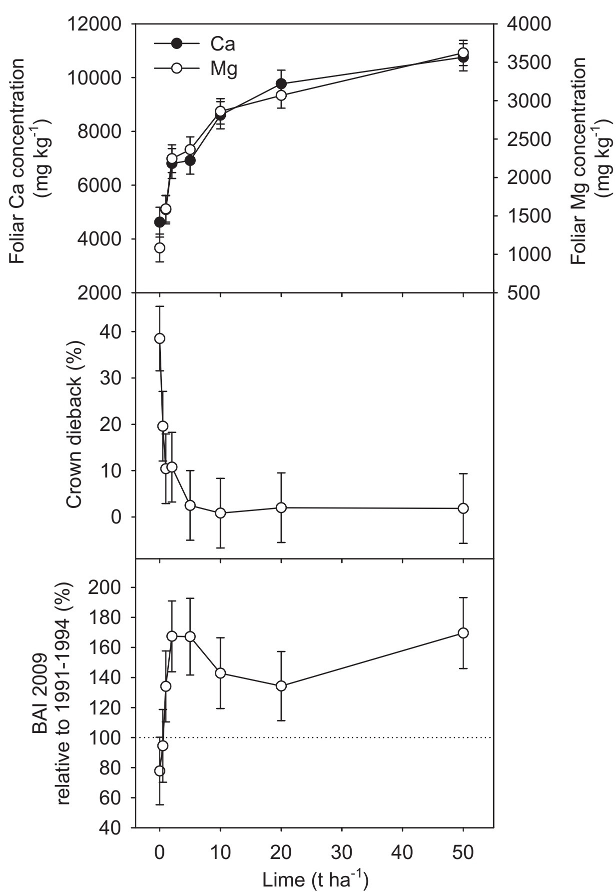

Fig. 1. Adjusted foliar Ca and Mg concentrations, crown dieback and basal area increment (BAI) of sugar maples in 2009 at Duchesnay. Error bars represent ±SE.

stem density increased with the lime rate (linear contrast $P = 0.012$, quadratic contrast $P = 0.060$), with the seedling density twice as large in the 50 $Mg\ ha^{-1}$ (32 seedlings m^{-2}) compared with the controls (16 seedlings m^{-2}). The lime rate also influenced the proportion of stems of SM, AB, and other species pooled together. The proportion of SM over all of the other species increased quadratically from 22% in the controls to more than 55% in the 5–50 $Mg\ ha^{-1}$ treatments ($P = 0.002$). In contrast, the proportion of AB and other species decreased with the lime rate. The proportion of AB in the treated plots was less than half the proportion observed in the controls (26%) ($P = 0.003$), while the proportion of other species decreased quadratically from 30% in the controls to less than 10% in the 10, 20, and 50 $Mg\ ha^{-1}$ treatments ($P < 0.001$). The proportion of SM stems present among the ten higher saplings also increased linearly with the lime rate ($P = 0.003$) (Fig. 6).

The effect of the lime treatment on the regeneration height and diameter of all species pooled together are presented in Fig. 7. On average, the seedling height and diameter decreased quadratically ($P \leqslant 0.013$), while the height and diameter of the ten taller saplings decreased linearly with the lime rate ($P \leqslant 0.016$). The seedling height and diameter were nearly two times greater in the control treatment compared with the 50 $Mg\ ha^{-1}$ lime treatment, while the sapling height and diameter decreased by 31% and 35%, respectively, between these two treatments.

4. Discussion

4.1. Soil response to liming

The soils still showed major differences with the lime rate 15 years after treatment. The magnitude of change in the forest floor after 15 years is similar to those observed 10 and 5 years earlier (Moore et al., 2008; Houle et al., 2002). Although the soils of this experiment were previously sampled in 1999 and in 2004, the sampling technique, depth of sampling, and time of year was different at each sampling time, and thus, the direct comparison

Table 2
Foliar nutrient concentrations for control and limed sugar maple trees at Duchesnay, 15 years after liming.

	Dolomitic lime (Mg ha^{-1})								*P* values			
	0	0.5	1	2	5	10	20	50	Treatment effect	Unlimed vs. limed trees	Linear contrast	Quadratic contrast
Foliar concentrations (mg kg^{-1})												
N	19,150	19,390	19,555	19,460	18,583	18,817	18,342	17,367	0.356	0.646	0.028	0.585
P	1,518	1702	1612	1743	1548	1591	1685	1797	0.104	0.073	0.033	0.870
K	6854	6673	6857	6030	5302	5897	5834	5285	0.031	0.068	0.015	0.462
Ca	4624	5754	5090	6595	6918	8600	9770	10,603	<0.001	<0.001	<0.001	0.014
Mg	1083	1402	1591	2244	2363	2861	3068	3621	<0.001	<0.001	<0.001	<0.001
Mn	797	939	855	720	807	509	507	300	<0.001	0.146	<0.001	0.111

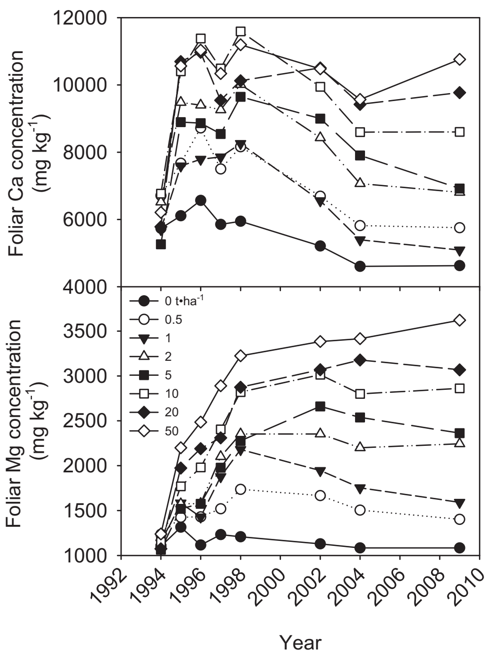

Fig. 2. Adjusted foliar Ca and Mg concentrations of sugar maples at Duchesnay over the 15 years of the liming trial.

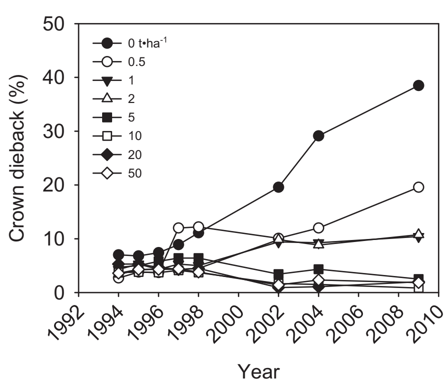

Fig. 3. Adjusted crown dieback of sugar maples at Duchesnay over the 15-year liming trial. Vertical lines over bars represent ±SE.

among the samplings shall be made with caution. Only the soil sampling in 1999 (in five of the eight lime treatments) (Houle et al., 2002) is somewhat comparable to the sampling made in 2009. In general, the forest floor kept the same concentrations of organic matter and exchangeable Ca, Mg, acidity and CEC with the lime treatment during the 10-year interval between the two samplings (1999–2009). However, the comparison of the mineral horizon properties during this 10-year interval shows a two fold increase in exchangeable base cation (Ca, Mg, K) concentrations and a corresponding reduction in exchangeable acidity. The differences in the mineral soil pH are also much greater among the lime treatments in the 2009 than in the 1999 sampling. However, no marked change in the trend over the 10-year interval occurred with organic matter concentrations versus the lime dose in this soil horizon. These changes suggest that the lime addition on the forest soil surface has taken more than a decade to reach and influence the exchangeable cation composition in the mineral soil, while the changes observed in the forest floor 5 years after treatment were still of the same magnitude 10 years later. These changes also suggest that the higher lime rates will have an even longer lasting effect on soils than the lower rates. As long as the biogeochemical processes are influenced by the lime treatment, including tree uptake and litter input through the leaf and fine-root turnover, the observed soil changes should remain apparent (Morrison and Foster, 2001).

4.2. Sugar maple response to liming

4.2.1. Nutrition

Fifteen years after the one-time application of lime in 1994, the treatment effect remained obvious in the foliage of the limed trees, particularly for the higher doses (Table 2; Fig. 1). The mean foliar concentrations of Ca and Mg in the limed trees were higher than those for the control trees by 65% and 126%, respectively. However, the foliar Ca concentrations of SM trees treated with the two lower lime doses (0.5 and 1 Mg ha^{-1}) were similar to the values of unlimed and pre-treated (1994) SM trees (Fig. 1), as reflected in the soil properties (Table 1). According to the SM nutritional values in other studies (cf. Moore and Ouimet, 2010), these Ca values were considered to be in the "unhealthy" range for SM health. Regarding the foliar Mg concentrations of SM trees for all lime doses in 2009, the concentrations were similar to those found in the healthy stands (cf. Moore and Ouimet, 2010). Long et al. (2011) also reported an increase in SM Ca (treated = 9519 mg kg^{-1}, control = 3913 mg kg^{-1}) and Mg (treated = 2855 mg kg^{-1}, control = 646 mg kg^{-1}) concentrations in the foliage 22 years following a one-time application of 22.4 Mg·ha^{-1} of dolomitic lime in Pennsylvania. These values are similar to those observed in our study for the 20 Mg·ha^{-1} doses (Ca: treated = 9770 mg kg^{-1}, control = 4624 mg kg^{-1}; Mg: treated = 3068 mg kg^{-1}, control = 1083 mg kg^{-1}).

The dolomitic lime application induced a negative effect on K nutrition, resulting in a decrease in the foliar K concentrations in limed trees (Table 2). This decrease was also noticeable in the soil exchangeable K values after 15 years. This negative effect was also reported for the SM in other studies after the application of dolomitic lime (Côté et al., 1995; Ouimet et al., 1996b; Long et al., 2011). Given the overall improvement in the crown vigor and growth of the limed SM trees in Duchesnay (see below), K was seemingly not a limiting factor for SM in this ecosystem, although

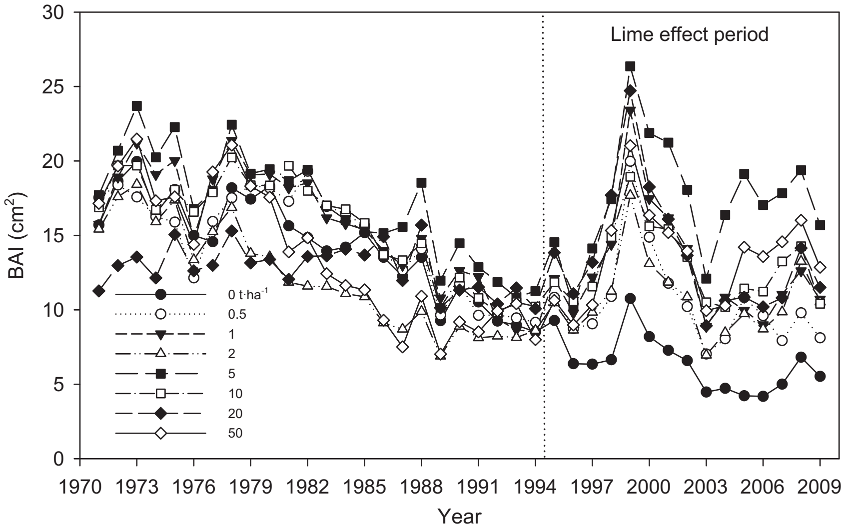

Fig. 4. Unadjusted mean annual basal area increment (BAI) of sugar maples at Duchesnay before liming and during the 15 years following liming.

the K nutrition was negatively affected. Moreover, no response of SM to the K application was detected in this SM stand (Moore and Ouimet, 2006). This result contrasts with other studies in Vermont (Wilmot et al., 1995) and the Quebec Appalachian range (Ouimet and Fortin, 1992), where foliar K was significantly related to SM vigor. These contrasting findings suggest that the nutrient requirements are site-specific and emphasize the importance of determining which nutrients limit sugar maple growth and health in a given ecosystem before applying the proper nutrient amendment (Ouimet et al., in preparation).

Manganese is an essential micronutrient, but high levels of foliar Mn have been associated with a decrease in the photosynthetic activity (McQuattie and Schier, 2000; St. Clair et al., 2005), root growth (St. Clair and Lynch, 2004), and vigor of SM (Kogelmann and Sharpe, 2006; Long et al., 2009, 2011). Additionally, in acidic soils, Mn can interfere with Ca and Mg uptake (Reisenauer, 1988). In Duchesnay, foliar Mn concentrations in the untreated SM ($\leqslant$ 1238 mg kg^{-1}) (Moore et al., 2000; Moore and Ouimet, 2006) are however much lower than the Mn values found in the unhealthy stands of northeastern North America (cf. Moore and Ouimet, 2010: median of 2400 mg kg^{-1}). Moreover, no relationship was detected between the crown dieback and the foliar Mn concentrations in this experiment. This finding suggests that Mn toxicity was not involved in the increasing crown dieback observed in Duchesnay. For the limed SM, reduction in the foliar Mn concentrations after 15 years (Table 2) is consistent with the observations made in another long-term SM liming study (Long et al., 2011).

4.2.2. Crown dieback

Fifteen years after the beginning of this experiment, crown dieback of the untreated SM trees reached 39% (Fig. 1). This value is 10% higher since the last measurement in 2004 (10 years after liming) and ten times higher than the first measurement in 1994. In addition, SM mortality was primarily observed for the unlimed trees. This major and rapid deterioration of SM health occurred despite that there was an effort in 1994, at the time of treatment application, to select the trees with no major trunk defects or significant dieback rate (mean of 4.3% dieback rate before treatment). Moreover, no strong triggering factor was observed during the 15 years after liming (Moore and Ouimet, 2006). However, well before the appearance of visual symptoms of dieback, the growth decline was observed for SM in this study (Fig. 4). Duchesne et al. (2003) have shown that a constant decrease in the BAI growth rate for 30 years could lead to the visual symptoms of crown dieback. As previously mentioned by Moore and Ouimet (2006), "the evidence suggests that the long-lasting predisposing factors prevailing at Duchesnay (low soil BS, Ca-poor soil, high acid deposition) can lead to sugar maple dieback and mortality without the presence of strong triggering factors". Hallett et al. (2006) also demonstrated that the nutritional imbalance (Ca, Mg, and Mn) alone is sufficient to cause a decrease in the stand health, but stands will be at risk of increased mortality only if other stresses occur. This finding emphasizes the need to develop tools to detect SM decline early, before the appearance of visual symptoms.

The lime application prevented the progression of SM decline symptoms in Duchesnay, even for the lowest doses (Fig. 1). However, the higher doses (5, 10, 20 and 50 Mg ha^{-1}) were seemingly more effective at preventing dieback than the lower doses. Other short- and long-term studies in the northeastern United States also reported an improvement in the SM vigor following liming (Wilmot et al., 1996; Long et al., 2011). In Ontario, Tominaga et al. (2008) showed that the risk of tree death increases with higher declining crown conditions. According to the pattern of SM crown dieback observed in Duchesnay (Fig. 3) and conclusions from Tominaga et al. (2008) and Duchesne et al. (2003), increasing mortality could be observed in the coming years for the untreated SM and, to a lesser degree, for the trees that received the lower lime doses.

4.2.3. Basal area growth

Liming still had a very strong and positive effect on the SM BAI in Duchesnay, 15 years after treatment (Figs. 1 and 4) even at a much lower lime rate than reported in a previous long-term liming study (Long et al., 2011). For the 2 and 5 Mg ha^{-1} doses, the BAI more than doubled (+114%) that of the unlimed SM trees. In Pennsylvania, Long et al., 2011 observed that the mean annual BAI was approximately 115% higher for the SM treated with 22.4 Mg ha^{-1} of dolomitic lime relative to the unlimed trees 21 years after treatment. In Duchesnay, the BAI increase for a similar dose (20 Mg ha^{-1}) was 70% 15 years following treatment. An increase in leaf photosynthesis from the higher leaf biomass (resulting from the increasing vigor) and the higher photosynthetic rates following the base cation addition (Ellsworth and Liu, 1994) may explain the positive effect of liming on the SM BAI observed in this study. Additionally, base cation fertilization can stimulate root colonization by arbuscular mycorrhizal fungi (Coughlan et al., 2000; St. Clair and

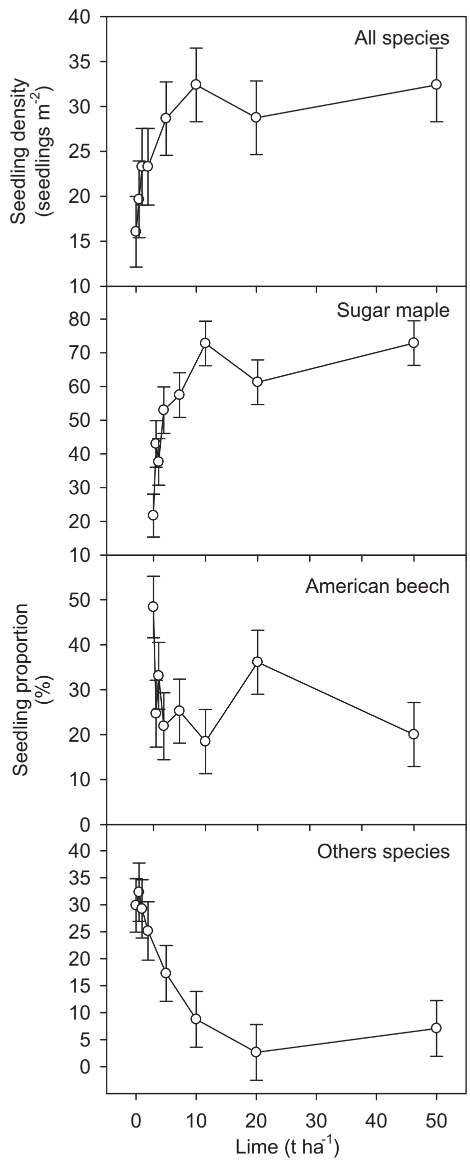

Fig. 5. Adjusted means of seedling density and proportion of sugar maples, American beeches, and all other species pooled together in the regeneration cohort at Duchesnay as a function of the lime rate. Error bars represent ±SE.

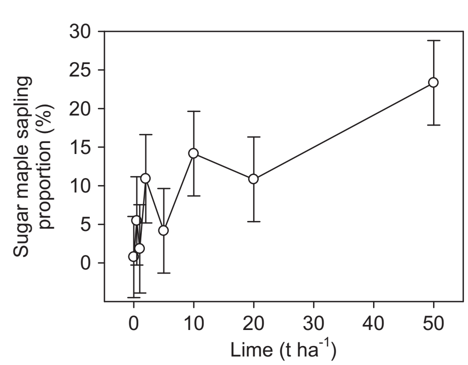

Fig. 6. Adjusted means of the proportion of sugar maple stems in the ten taller saplings in the regeneration cohort at Duchesnay. Error bars represent ±SE.

Lynch, 2005; Juice et al., 2006), which can stimulate SM nutrition, health and, consequently, growth.

Normally, tree growth should decline progressively with stand closure following fertilization or liming given the increase in competition among trees. In this context, we should expect a weaker response of tree BAI when liming is performed at the stand level. However, Long et al. (2011) showed that the long lasting effect of lime may persist for more than 20 years when the stand basal area is low. In our study, the long-lasting and beneficial effects of liming on BAI of individually limed trees showed that they were not or little affected by any competitive effects from surrounding SM trees.

The persistently strong effect of liming on the soil and foliar Ca and Mg concentrations (Table 1, Fig. 2), vigor (Fig. 3), and basal area growth (Fig. 4) indicates that this treatment will likely remain effective for many years, at least for the higher doses. However, the effects of lower doses (0.5, 1, 2 Mg ha^{-1}) on SM vitality appear to be decreasing in recent years. These results provide valuable information for the maple syrup producers who encounter similar vitality problems in their sugarbush, suggesting that a lime dose ranging between 2 and 5 Mg ha^{-1} should remain effective for at least 15 years for a similar ecosystem.

4.2.4. Regeneration

The increase in the relative density of SM in the seedling and sapling stratum indicates that the lime application has been beneficial for the establishment and growth of SM regeneration. Our observations are consistent with other studies reporting the beneficial effects of Ca addition on the survivorship and abundance of SM regeneration (Long et al., 1999, 2002; Juice et al., 2006; Zaccherio and Finzi, 2007). Previous studies have suggested that soil calcium may be a limiting factor in SM seedling survival in forests with low soil calcium (Jenkins, 1997; Long et al., 1999; Duchesne et al., 2005; St. Clair and Lynch, 2005; Juice et al., 2006; Bigelow and Canham, 2007). The declining recruitment of SMs in the Adirondacks (Jenkins, 1997), New Hampshire (Hane, 2003; Juice et al., 2006), and Quebec (Duchesne et al., 2005; Moore et al., 2008) has been attributed, among other factors, to the sensitivity of seedlings to the soil cation depletion from acid deposition (Park and Yanai, 2009).

Availability of light and soil resources are two important factors governing regeneration. In our study, the addition of lime improved the acid–base status of soil (Table 1). Concurrently, the lime treatment improved the vigor of overstory trees, reducing light availability in the understory (Moore et al., 2008). These two major processes acted together to govern the ecological response of regeneration to the lime treatments. Despite a marked increase in the density of SM regeneration with the lime rate, height and diameter of seedlings and saplings were, on average, inversely correlated with lime rate 15 years following liming (Fig. 7). This could have been the result of (1) an increase in stem density of regeneration with lime rate, which may have increased the competition for space and soil resources and limit the development of the regeneration or (2) higher canopy closure under the limed trees that could have limited the development of the regeneration (Figs. 1 and 3).

4.3. Perspective on Ca availability in SM stands

According to many studies, Ca depletion from soils of northern hardwood stands with a low acid-buffering capacity is anticipated to continue, in part, because of the effect of acid deposition (Likens et al., 1998; McLaughlin, 1998; Houle et al., 1997; Sharpe, 2002; Bailey et al., 2005; Long et al., 2009). While sulfur emissions have been decreased by half over the last 20 years in the northeastern US, global atmospheric N deposition are projected to more than double in the next century (Galloway et al., 2004).

In a SM stand neighboring the liming experiment, foliar Ca concentrations of SM decreased by 12% relative to controls during the first 3 years after application of only 16 kmol H ha^{-1} in the form of

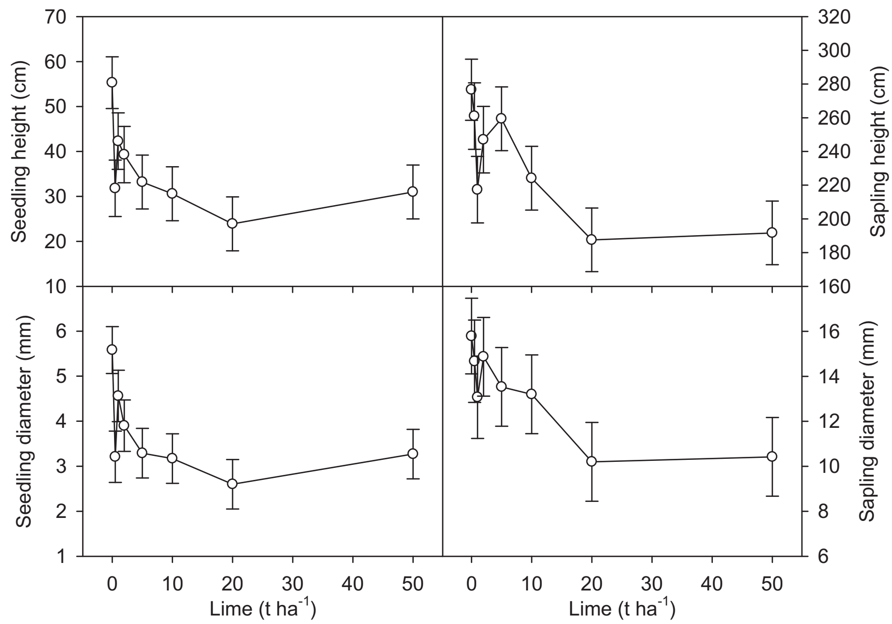

Fig. 7. Adjusted means of seedling and sapling height and diameter of all species pooled together at Duchesnay. Error bars represent ±SE.

elemental sulfur (Ouimet et al., 2008). In another SM stand neighboring the liming experiment, 8 years of repeated nitrogen fertilization caused a decrease in foliar Ca concentrations to values as low as 3737 and 2325 mg kg^{-1}, for the low (representing 24 years of N deposition) and high N treatment (representing 80 years of N deposition), respectively, while the control trees had foliar Ca concentrations of 4229 mg·kg^{-1} (Moore and Houle, in preparation). The foliar Ca concentrations in the N-treated plots were the lowest reported in the literature for SM and are well below the foliar concentration threshold reported for healthy SM (cf. Moore and Ouimet, 2010). These results support the theory that acid deposition in future years can accentuate the Ca nutrition imbalance for SM in base-poor soils. In this context, liming is currently the only known treatment which clearly demonstrated the possibility to reverse this trend.

Given the high sensitivity of SM to Ca availability and soil acidity, the use of other Ca fertilizers, such as wood ash, may also be promising. In Europe, wood ash has been used in the last decades, mainly in coniferous forest, to mitigate the effect of acid deposition in forest soils (Augusto et al., 2008). However, the effect of wood ash on SM vitality is still not well documented (Feldkirchner et al., 2003).

4.4. Forest management implications

A growing number of studies have documented changes in the forest dynamics of some SM-dominated stands toward more AB-dominated stands attributed to soil acidification and Ca depletion (Jenkins, 1997; Kobe et al., 2002; Duchesne et al., 2005; Bigelow and Canham, 2007; Duchesne and Ouimet, 2009) by slowing the growth of Ca-demanding species, such as SM, and promoting the growth of the low-Ca tolerant species, such as AB (Bigelow and Canham, 2007).

In Duchesnay, the base-poor soil status (Houle et al., 1997; Moore et al., 2008), poor SM vitality (Moore and Ouimet, 2006) and the increased abundance of pole size AB (Duchesne et al., 2010) have already been documented. These findings indicate that the shift in forest dynamics toward a more AB-dominated stand is already occurring in this ecosystem. To mitigate the increase in abundance of AB regeneration at the expense of SM in base-poor SM stands, the effects of cleaning the understory (providing 1 m of crown expansion space around evenly distributed saplings) and soil liming on growth of the SM and AB sapling cohort is being tested experimentally in Duchesnay (Duchesne et al., accepted for publication). The preliminary results show that the combination of liming and cleaning of the SM saplings was the only treatment that provided a competitive advantage to SM compared with the uncleared AB saplings.

From an economic perspective, increase in the abundance of AB in SM-dominated stands may be deleterious because of its low value compared with SM. Moreover, SM has been exploited for maple syrup, for which the province of Quebec is the largest producer, accounting for approximately 80% of the world production (Gouvernement du Québec, 2009). Thus, preserving the SM component in SM stands is particularly important for the maple syrup producers who have made important infrastructure investments.

5. Conclusion

This study shows that a single and appropriate lime addition can correct the base cation deficiencies in base-poor and declining northern hardwood stands. This treatment also has strong and long-lasting beneficial effects on the SM nutrition, vigor, growth and regeneration. In this context, liming appears to be an essential tool to restore SM representation and stand health in acidic and base-poor soils. However, if the objective is to provide a competitive advantage for SM over AB in the stands where a marked increase in the abundance of AB saplings is observed, liming should be coupled with SM cleaning and with the reduction of the AB component in the sapling stratum (Duchesne et al., accepted for publication).

Acknowledgments

This research was supported by the *Ministère des Ressources naturelles et de la Faune du Québec* (Project No. 112310063). We wish to thank Claude Camiré of Université Laval, who supervised the implementation of the experimental setup, Benoît Toussaint, Jacques Martineau, Jean Gagné, and Mario Saint-Germain for field assistance, the personnel of our *Laboratoire de chimie organique et*

inorganique for performing the numerous analyses, and Isabelle Auger for statistical advice.

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